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CONTRACT REPORT NO. 1SQ83-00025

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TITLE "DEVELOPMENT AND IMPLEMENTATION OF A GENERAL PURPOSE SIGNAL ANALYSIS SYSTEM FOR NON-DESTRUCTIVE TESTING (NDT) BASED UPON PATTERN RECOGNITION (UP-T-171)"

CONTRACTOR: TEKTREND

March 6, 1985

Dr. Jean-Pierre Monchalin
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Re: Development and Implementation of a General Purpose Signal Analysis System for Non-Destructive Testing (NDT) based upon Pattern Recognition (UP-T-171).

Dear Dr. Monchalin:

This is the final report for the above referenced project. As agreed, the reporting requirement would be met by the preparation of SCANS manuals and of reports for publication in the open literature. Two such manuals have been prepared:

* Theory of Operation
* Users Manual

and two reports prepared for publication in collaboration with you and Dr. Jean Bussière of IGM:

* Ultrasonic Welding Defect Sizing by Advanced Pattern Recognition Techniques.

* Defect Characterization and Sizing in Pipeline Weldments by Analysis of Ultrasonic Echo Features.

As agreed ten copies of these documents are supplied with this report in satisfaction of contractural requirement as opposed to the 50 copies requested in the contract.

23 pp

MICROMEDIA

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In addition, SCANS has been implemented and tested on the IGM VAX. We remain available for support of the system and welcome your suggestions for improvements.

Enclosed is our final claim for this contract.

Yours sincerely,

D R. Hay

Dr. D. Robert Hay
President

Enclosures

ULTRASONIC WELDING DEFECT SIZING

BY ADVANCED PATTERN RECOGNITION TECHNIQUES

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INTRODUCTION

Ultrasonic flaw sizing based on signal analysis and classification techniques was applied to linear welding flaws of sizes ranging from 1mm to 3mm generated under controlled laboratory conditions. Over 400 ultrasonic signals were captured digitally at various positions along these linear flaws and analyzed by an advanced pattern recognition package with regard to flaw sizes. Very encouraging results were observed and in some cases 100% correct flaw sizing performance has been achieved.

BACKGROUND

With the rapid increase in computational power, highly automated, computer-based systems are appearing in the field of ultrasonic inspection of plates, billets, forging pipes, tubing and welded joints. Recently the demand for increased material performance has led to greater requirements for more detailed information about nondestructively detected defects. There are many cases where precise flaw location is not sufficient; defect size, shape, orientation and composition should be determined so that the effects of the flaw on material properties can be estimated. For very large defects, some of these characteristics can be measured or estimated by transducer scanning; however, for smaller, but still important defects, less direct methods of flaw characterization are required. Signal processing and pattern recognition techniques applied to ultrasonic signals have emerged as a means of accomplishing flaw characterization. Methods such as signal averaging, filtering and correlation have been used to extract weak signals from

incoherant noise; deconvolution have been applied to improve system resolution; deconvolution and spectral analysis have been used together to elicit flaw characterization information from ultrasonic echoes, and pattern recognition techniques are applied to distinguish among the family of flaws by utilizing the characterization information. A number of general applications of signal processing to ultrasonic non-destructive evaluation has been reported by Erikson et al. (1), Kennedy and Woodmansee (2), and Rose and Meyer (3,4). Pattern recognition techniques for classification of ultrasonic and similar categories of signal have been successfully applied by us (5-9). An exhaustive survey of ultrasonic signal applications, techniques and instruments has been compiled by Silvus (10).

Recent approaches to the flaw classification problem which are specifically based on signal analysis of amplitude-time, frequency or phase profiles have proven useful in a few applications discussed above. Generally the signal approach is tedious, time consuming, and undependable (5). Signal processing techniques combined with pattern recognition techniques, however, have shown great potential in flaw analysis.

Generally, a pattern recognition system goes through a learning stage, in which a set of decision rules is developed. Parameters which can be used to distinguish signals from known reference samples are identified. Many researchers are addressing the problem of how to adequately determine the important parameters of an ultrasonic instrumentation system. It is not necessary to go into the detail of how each of the parameter should be measured. It is more important to examine the methods for measuring parameters in terms of the objectives of the measurement. A number of such parameters are listed in (11). The parameters selected are described later. Based on the parameters chosen, a number of decision rules can be set up, and the system trained on them. The system is said to be "trained" when it can use the decision rules to identify an input signal. To test the performance of the trained system, sample signals not used during the training process are presented to the system, which attempts to identify the class to which each unknown signal belongs. Successful identification of input signals is a good indication of a properly trained system. In this paper, a more challenging problem has been attempted to apply pattern recognition techniques to size weld defect of the same origin with resolution in the 1mm range.

THE EXPERIMENT

Linear welding flaws were generated by welding two 5" x 9" A-36 mild steel plates with 1/2" thickness side by side from both surfaces as depicited in Figure 1.

Flaws with sizes ranging from 1mm to 3mm were generated intentionally near the center of the weldment. A total of four samples were prepared for this study (Table 1). These

samples were then presented to an ultrasonic inspection facility at the National Research Council of Canada - Industrial Material Research Institute. An immersion pulse-echo method was used to capture signals at various postions along these linear welding flaws. The sample was placed in a water tank and a computer controlled robot arm was used to position the transducer at the proper position with pre-determined height and incidence angle with respect to the flaws (Table 2). Two types of transducers were used in this study, an ULTRAN/L-50-5 flat transducer with nominal frequency of 6.6 MHz and an ULTRAN/L-50-5-P4 focused transducer with nominal frequency of 5.0 MHz. The sample was pulsed by a METROTEK MP215 pulser with maximum amplitude and damping and received by a METROTEK MR101 receiver with filter setting of 0.5 MHz. This received signal was then digitized through a TEKTRONIX 7854 digital scope with a sampling speed of 100 MHZ using equivalent time sampling. A total of 512 data points were gathered per signal. This signal was then transferred to external storage device for further analysis. 425 signals were gathered and Table 3 summarizes the distribution of these signals with regard to the defect size and test sample geometry.

ANALYSIS OVERVIEW

The ultrasonic signals were analyzed using an advanced signal processing and classification package - SCANS (System for Classification and Analysis of Non-destructive-testing Signals). The SCANS system has already been demonstrated to be capable of identifying signals from different types of flaws (6,8). For this study, we apply SCANS to differentiate signals originating from the same type of flaw, but with different flaw sizes. It is quite a subtle analysis because these signals bear very similar information. Before pattern recognition techniques can be applied, the original digitized signal must be transformed into a list of descriptors or "features". For successful classification to take place, these features should bear pertinent information either explicitly or implicitly related to the physical phenomena distinguishing the classes of defect to be recognized. Since there is no a priori knowledge of the best descriptors to use with regard to our problem, many types of waveform parameters derived from the original signal are used in this study. A total of 87 features are available for this analysis including features in the time domain, pulse shape information, power distribution in the frequency domain, auto correlation and cepstral information (Table 4). The 425 signals collected for this test are grouped according to their defect size and geometry, and they are further divided into two sets, one set of signals is used to train the SCANS classifier to recognize the signals based on their defect sizes and the other set is used to verify the performance of this classifier.

A series of tests are designed to explore the feasibility of using pattern recognition techniques to size weld defects with very fine resolutions (around 1mm).

As mentioned in the previous section, the experiment involves the collection of immersion pulse/echo ultrasonic signals. The pulser is held at a controlled height and angle with respect to the sample defect and, for greatest success in sizing the flaws, these two parameters should be held constant throughout training and testing. In applications, however, the height and incidence angle may fluctuate to some degree, so besides testing sizing performance under ideal conditions, problems designed to determine the immunity to these types of positioning errors are included. This immunity is examined through two types of test. In one, various heights or incidence angles are grouped together as a single class during testing and training. In the other, training is conducted at a fixed height or angle, but testing is done at different values than those used in training. Finally, to determine that the flaw size is being recognized, as opposed to other characteristics of the specimen, problems are included in which the classifier is trained to distinguish between different-sized defects in one pair of samples, and then tested on a different pair of samples containing the same sized defects.

PROBLEMS

The experimental problems are outlined in the following paragraphs and the corresponding results are summarized in Table 5 and Table 6.

PROBLEMS 1 - 4 : FLAT TRANSDUCER

Problem 1: Flaw sizing from a fixed angle

The classifier was trained to distinguish between flaws of [1mm and 2mm], [1mm and 3mm], and [2mm and 3mm] width. The data presented to the classifier was obtained at a fixed height and incidence angle of the incident ultrasonic transducer with respect to the sample.

The fixed incidence angles used were 18.9°, 23.2°, and 26.2° in the water and corresponding to 45.0°, 60.0° and 75.0° inside the test specimens.

Problem 2: Flaw sizing from a constant angle, trained on one specimen and tested on a second specimen.

Two specimens containing 3mm flaws were available, one 10" x 5" x 1/2", and the other 10" x 9" x 1/2".

The classifier was trained to distinguish between flaws of [1mm and 3mm], and [2mm and 3mm] on data obtained from the first 3mm defect specimen. The trained classifier was then tested on the same flaw sizes, but using data from the second 3mm defect specimen.

Again, incidence angles were fixed, and the problem was conducted at angles of 18.9°, 23.2° and 26.2°.

Problem 3: Train on one angle and test on a different angle.

The classifier was trained to distinguish between flaws sized [1mm and 2mm], [1mm and 3mm], and [2mm and 3mm].

The training data for both flaw sizes was obtained at an incidence angle of 18.9°. The classifier was tested on data obtained from the same flaws at an incidence angle of 23.2°.

Problem 4: Flaw sizing: Train and test using mixed incidence angles, i.e. independant of incidence angle.

The classifier was trained and tested to distinguish between flaws of [1mm and 2mm], [1mm and 3mm], [2mm and 3mm] on independent sets of data combining all the incidence angles available. (18.9°, 23.2°, 26.2°).

PROBLEMS 5 - 9: FOCUSED TRANSDUCER

Problems 5,6,7, and 9 :

These problems for the FOCUSED transducer correspond to Problems 1,2,3, and 4 for the FLAT transducer.

The incidence angles are identical in both cases, with the following addition: As well as including the transducer positions 18.9° at 80mm height, 23.2° at 30mm height, and 26.2° at 70mm height, data was also available at 23.2° at 75mm height. Therefore, for the focused transducer, more results are presented for problems 5 and 6 than for problems 1 and 2, corresponding to this extra group of data.

This extra group of data also allows the addition of another problem: Problem 8, in which the angle of the transducer remains constant through training and testing, while the height changes.

The classifier was trained to distinguish between flaws of [1mm and 2mm], [1mm and 3mm], and [2mm and 3mm] for transducer position of 23.2° incidence angle and 30mm height.

The focused transducer experiments are summarized below.

Problem 5: Flaw sizing from a constant angle.

Problem 6: Flaw sizing from a constant angle: Train on one and test on a different sample.

Problem 7: Flaw sizing: Train on one angle and test on another.

Problem 8: Flaw sizing: Train on one height and test on a different height.

Problem 9: Flaw sizing: Train and test using mixed angles i.e. independent of incidence angle.

INTERPRETATION OF RESULTS

Based upon the result of the analysis, the following has been observed:

1. There is no significant effect on the flaw sizing results due to transducer type differences. As shown in Table 5 and 6, both experiments show high consistency in sizing flaw when all other controllable parameters are kept constant.

2. Very encouraging recognition rates (over 90%) have been achieved to size flaws with 2mm resolution and the percentage goes down to a mid 80% when the resolution is increased to 1mm. This phenomenon can be accounted by the fact that although the simulated defects were generated under very carefully controlled environment to ensure that the flaw sizes were uniform and close to the decimal values, there remains some as yet uncharacterized scatter in flaw size which will contribute to the uncertainty in recognition.

3. The height and incidence angle from which the ultrasonic signals were gathered show significant effect on the sizing preformance and it usually reduces the recognition rate between 10 to 15%. However, a classifier trained on one specimen will perform well when applied to size flaw from a different specimen even if the geometry of the specimen is different as long as the signal is gathered with the same height and incidence angle as used in the training specimen.

CONCLUSION

The results of this study suggest advanced pattern recognition techniques can be applied to sizing flaws with very high consistency. The recognition results presented could further be enhanced by optimizing the set of features used for classification. Such optimization was not attempted in this study.

The external unknowns that affect the recognition results are those governed by how the data are gathered, such as incidence angle and height, but not those inherent with the specimen being tested, such as geometry. However the transducer type differences show no significant effect on the sizing result provided the transducer type used in both training and testing signal collection are the same. This implies a flaw detection and sizing system can be trained using a known defect and later applied to recognize unknown flaws from a totally different specimen without loss of generality.

ACKNOWLEDGEMENT

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FIGURE 1

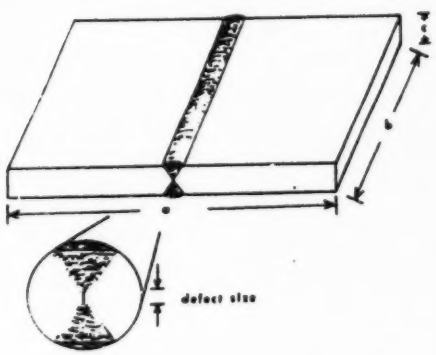

TABLE 1

SAMPLE	DIMENSIONS			DEFECT SIZE
	a	b	c	
1	10"	5"	1/2"	3 mm
2	10"	9"	1/2"	2 mm
3	10"	9"	1/2"	3 mm
4	10"	9"	1/2"	1 mm

TABLE 2

	HEIGHT above the sample	ANGLE of incidence
FLAT TRANSDUCER	30 mm	18.9°
	22 mm	23.2°
	22 mm	26.2°
FOCUSED TRANSDUCER	60 mm	18.9°
	30 mm	23.2°
	76 mm	23.2°
	70 mm	26.2°

TABLE 3

TYPE	SPECIMEN				INCIDENCE	HEIGHT
	1	2	3	4		
FOCUSED	6	20	12	20	18.9°	60 mm
	8	12	12	12	23.2°	30 mm
	8	20	12	20	23.2°	76 mm
	8	20	12	20	26.2°	70 mm
FLAT	8	12	12	12	18.9°	30 mm
	8	12	12	12	23.2°	22 mm
	8	12	12	12	26.2°	22 mm

TABLE 4

FEATURE SET MAKE-UP

Domain	General Features	Shape Features	Power Distribution Features	Total Features
Time	6	30	0	36
Power	3	6	8	17
Cepstrum	3	6	8	17
Autocorrelation	3	6	8	17
Total Features	15	48	34	87

TABLE 5

PROBLEM 1			
	18.9	23.2	26.3
1mm vs 2mm	91.67	83.33	91.67
1mm vs 3mm	100.00	91.67	91.67
2mm vs 3mm	75.00	91.67	83.33
PROBLEM 2			
	18.9°	23.2°	26.3°
1mm vs 3mm	100.00	80.00	80.00
2mm vs 3mm	100.00	80.00	80.00
PROBLEM 3			
TRAINED ON 18.9°, TESTED ON 23.2° INCIDENCE			
1mm vs 2mm		87.50	
1mm vs 3mm		75.00	
2mm vs 3mm		62.00	
PROBLEM 4			
1mm vs 2mm		77.78	
1mm vs 3mm		95.00	
2mm vs 3mm		72.22	

TABLE 6

PROBLEM 5				
	18.9°	23.2°(30mm)	23.2°(75mm)	26.3°
1mm vs 2mm	90.00	83.33	80.00	85.00
1mm vs 3mm	93.75	91.67	93.75	93.75
2mm vs 3mm	81.25	75.00	75.00	81.25
PROBLEM 6				
1mm vs 3mm	100.00	90.00	83.33	87.50
2mm vs 3mm	78.57	70.00	83.33	71.43
PROBLEM 7				
TRAINED ON 18.9°(80mm), TESTED ON 23.2°(75 mm)				
1mm vs 2mm		80.00		
1mm vs 3mm		90.62		
2mm vs 3mm		84.37		
PROBLEM 8				
TRAINED ON 23.2°(75mm), TESTED ON 23.2°(30mm)				
1mm vs 2mm		75.00		
1mm vs 3mm		87.50		
2mm vs 3mm		83.33		
PROBLEM 9				
1mm vs 2mm		80.56		
1mm vs 3mm		95.00		
2mm vs 3mm		81.67		

Defect characterization and sizing in pipeline weldments by analysis of ultrasonic echo features. +

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ABSTRACT

Information on defect type (planar or volumetric) and on defect size can be obtained by analysis of ultrasonic echo features. We report progress made in the analysis of echos from planar weld defects, in the identification of diffracted and converted waves and in defect classification using pattern recognition algorithms.

INTRODUCTION

State of the art in ultrasonic NDT is now such that to detect signals from flaws is not generally a problem. However, the problem, which still arises in practice when an indication is observed, is to be able to classify the flaw as planar (such as a crack or a lack of side wall fusion) or volumetric (such as an inclusion or porosity), since the former kind is more likely to propagate under stress and to lead to catastrophic failure. If a planar flaw has been identified, it is also important to be able to size it or, at least, to be able to classify it among benign or critical sizes, the threshold value being given by a fracture mechanics analysis of the structure under inspection. In some cases, where a flaw is likely to occur near a geometrical reflector, (e.g. a corner, crown of a weld) it is also important to distinguish unambiguously its indication from that of the geometrical reflector. It is known that the nature and the size of defects translate into characteristic features of ultrasonic echos received from flaws. The problem is then to find a correspondance between a feature or group of features and a flaw parameter.

To find this link, two approaches may be considered: one consists in understanding the physics of the interaction of ultrasound with the flaw and obviously can only be carried out for simple and idealized flaws, the other one consists in using pattern recognition algorithms working on empirically selected features and a data base from flaws already characterized (1,2). This last approach is general and computer programs can be written for automatic recognition. Its drawback is the empirical nature which may result into its inefficiency (long computing time) and inaccuracy (poor recognition probability). For critical flaws in high risk industries, probabilities close to 100% are required. This technique could be improved if the results of the first theoretical approach are used: more significant features may be found and a theoretically generated data base may replace the one obtained from a large number of characteristic flaws produced with difficulty and at high cost (3). CANMET, IMRI and Tektrend Inc. are working collaboratively on a defect

characterization program based on these lines. Classification uses the algorithms based on a linear discriminant function, an empirical Bayesian classifier and a K-nearest neighbor method previously developed for acoustic emission by Tektrend Inc. In this paper, we report preliminary work made on this project, the application being considered at the beginning being the characterization and sizing of pipeline weld defects.

EXPERIMENTAL

Since the application considered first in this program is pipeline welds, samples with defects were prepared from 1/2 inch (12.5 mm) thick steel plates. Planar flaws were obtained by butt welding two plates laid side by side: one weld pass was made with insufficient penetration, then the plates were turned upside down and a second pass was made, leaving in the middle an unfused area, running the whole plate length. In this way, planar defects, which perfectly simulate internal lack of side wall fusion, were obtained. Long defects (10 inches or more) having uniform through-wall dimension of ≈ 1, 2 and 3 mm were obtained. A flaw of 1 mm or less is generally considered as benign whereas larger flaws are considered critical (1).

Four plates (labelled #3, #4, #5 and #6) were made in this way and then cut in half. One half of each plate was machined to remove the weld crown, whereas the other half was left unaltered. Defect size was measured visually from both ends of the plates. The following results were found:

Plate # 3:	2.75 mm - 3 mm
Plate # 4:	2 mm - size not well defined from one side
Plate # 5:	3.5 mm - 3 mm
Plate # 6:	1 mm - 1 mm

Experimental data were taken from these samples at several locations along the defect using the pulse-echo immersion technique and broad-band commercial transducers at 5 MHz. Both planar and focused transducers were used with incidence angles of 45°, 60° and 75° in steel. Transducer height was adjusted in order that the defect was in the far field region of the planar transducer or in the focal zone of the focused transducer. The position of the transducer along the direction perpendicular to the defect was determined by maximizing the echo height for the planar transducer and somehow by trying to observe the maximum number of peaks with the focused one. The signal echo was digitized using a digital oscilloscope and the data was then stored for further computer processing. So far data has only been taken from the plates with the crown removed.

DISCUSSION OF OBSERVED ECHO FEATURES

The data taken with the planar transducer at 45° and 75° do not present any readily obvious distinguishing features, except some higher frequency oscillation at ≈ 7 MHz for the 3 mm defects at 45°. At 60°, trailing pulses are observed. The transducer being well damped poor signal-to-noise ratio is encountered and diffracted edge waves as predicted by elementary theory could not be clearly observed: theory predicts for a vertical defect that two pulses

separated in time by $2d \cos r / v_s$ should be observed where d is the defect size, r is the refraction angle in steel and v_s is the shear velocity. This time interval amounts to about 1.4 μs, 1 μs and 0.5 μs for a 3 mm defect at 45°, 60° and 75° refraction angle, respectively.

With the focused transducer properly adjusted, a much higher signal-to-noise ratio was obtained and several pulses could be observed as shown in figs. 1, 2 and 3 obtained at 60° with plate #3, plate #4 and plate #6, respectively. The first two pulses can be linked to shear waves diffracted by the edges and the observed time delay corresponds approximatively to that given by elementary theory (these pulses can be hardly separated for the 1 mm flaw sample). The other peaks which follow (one or two are observed) are linked to conversion into a compressional wave, to reflections of this wave by the surfaces of the plate and reconversion into a shear wave. This phenomenon was demonstrated by using a second compression transducer (planar) oriented normally to the plate and located right above the defect (see fig. 4). Using this transducer in a pitch-catch mode, the multiple reflections of the converted compressional wave can be seen as shown in fig. 5. The first pulse seen with this transducer is produced by a parasitic wave directly scattered from the first surface. Further evidence was obtained by milling a layer of constant thickness from the bottom of the plate. The periodic spacing observed with the compression transducer was observed to diminish by a time interval corresponding to the propagation of a compressional wave through the removed thickness. In the same way, the time interval between the two edge pulses and the third echo (also the fourth when observable) was decreased by the same amount. The converted wave was observed to be very strong at the 60° incidence angle and was generally very weak at 45° and 75°. This observation is consistent with the fact that 60° corresponds to 30° incidence on the defect surface which is close to the limit angle for longitudinal wave generation. It should be noted that in the experiments conducted so far, the weldment crowns were machined off. In the presence of the crowns, the use of the second transducer is not obviously possible and the crowns may diminish or enhance the conversion into shear waves observed in pulse-echo according to their shapes. Experiments are planned to observe the effect of the weld crowns.

CLASSIFICATION BY PATTERN RECOGNITION

Using the classifier and the features extraction programs developed by Tektrend Inc., we have analyzed about 400 ultrasonic signals taken as mentioned above from the 4 samples, at 45°, 60° and 75°, with a planar and with a focused transducer. The collected signals for each experimental setup (angle and transducer) were grouped according to their defect size and geometry, and they were further divided into two sets; one set of signals was used to train the classifier to recognize the signals based on their defect sizes and the other set was used to verify the performance of this classifier. The tests performed are indicated below with the recognition rates (expressed as percentages):

1. Planar transducer:

1.a. Signals from plate #3 and plate #5 are taken together as signals representative of a 3 mm flaw.

	45°	60°	75°
1mm vs 2mm	91.67	83.33	91.67
1mm vs 3mm	100.00	91.67	91.67
2mm vs 3mm	75.00	91.67	83.33

1.b. The classifier was trained on signals from plate #3 and then tested with signals from plate #5.

	45°	60°	75°
1mm vs 3mm	100.00	80.00	80.00
2mm vs 3mm	100.00	80.00	80.00

2. Focused transducer: (same tests as above)

2.a Signals from plate #3 and plate #5 are taken together as signals representative of a 3mm flaw.

	45°	60°	75°
1mm vs 2mm	90.00	80.00	85.00
1mm vs 3mm	93.75	93.75	93.75
2mm vs 3mm	81.25	75.00	81.25

2.b The classifier was trained on signals from plate #3 and then tested with signals from plate #5.

	45°	60°	75°
1mm vs 3mm	100.00	83.33	87.50
2mm vs 3mm	78.57	83.33	71.43

These classification results show that 100% recognition rates can be obtained in some cases. Also, they show that a resolution of 1mm in size which is required by fracture mechanics analysis is possible. Worse recognition rates are likely to be caused by a variation of the flaw size at the location where the data is taken. This problem will be resolved later when the samples will be sectioned. Also work is required to elucidate what are the most significant features for the planar transducer data as well as the focused one.

CONCLUSION AND PERSPECTIVES

We have reported preliminary work on sizing of planar weld defects by ultrasonic echo feature analysis. With proper ultrasonic excitation diffracted edge waves were observed and found to be easily interpretable for sizing. However, in many cases, the echo pattern is complicated by other phenomena. In particular, this work has shown that the flaw cannot be considered as isolated since interactions with the sample boundaries produce extraneous features which have to be taken into account. We have also shown that classification of planar flaws according to size can be accomplished with high recognition rates and resolutions of ≈ 1 mm. The approach presented therefore has a good potential for practical applications such as distinguishing between benign and critical flaws in pipeline weldments.

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FIGURE CAPTIONS

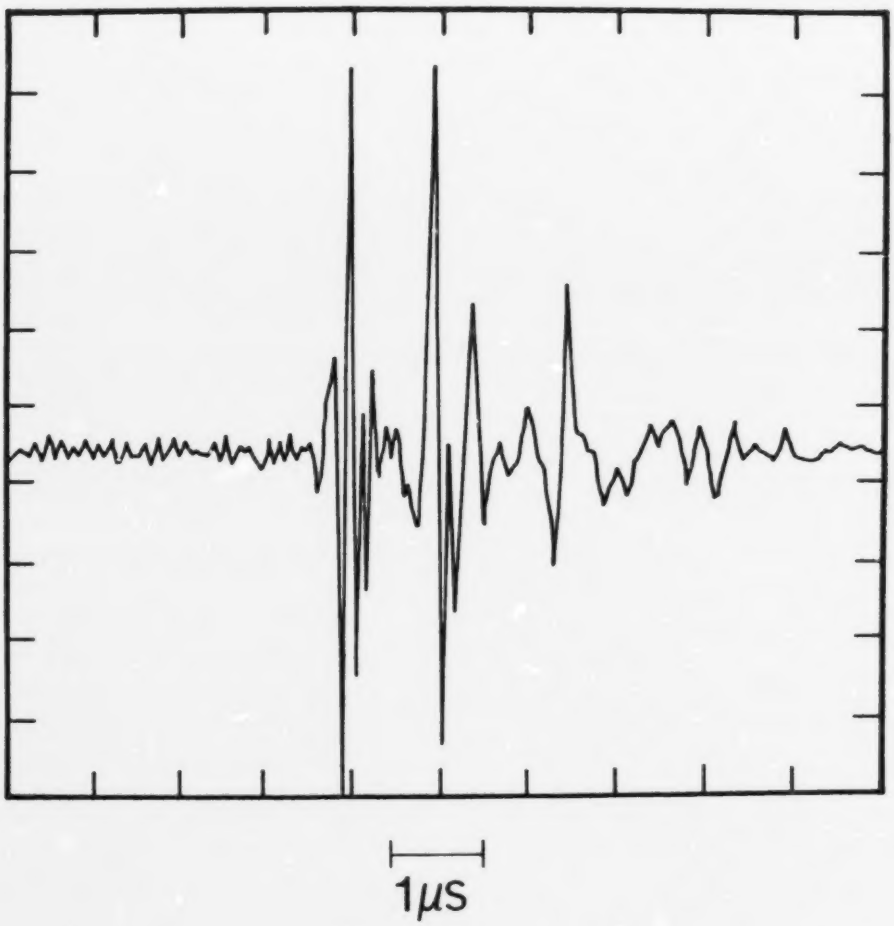
Fig. 1 Echos observed from plate #3 (vertical planar defect, = 3 mm) refraction angle in the plate = 60°, 5 MHz focused transducer.

Fig. 2 Echos observed from plate #4 (vertical planar defect = 2 mm), refraction angle in the plate = 60°, 5 MHz focused transducer.

Fig. 3 Echos observed from plate #6 (vertical planar defect = 1 mm), refraction angle in the plate = 60°, 5 MHz focused transducer.

Fig. 4 Experimental set-up to observe diffracted and converted waves.

Fig. 5 Oscilloscope traces observed with the transducers shown in figure 4. Top: pulse-echo signal from angled transducer - (the first pulse is parasitic). Bottom: echos from transducer directly above flaw - the first pulse is a direct reflection from the top surface, following pulses are reflections of mode-converted wave inside the plate.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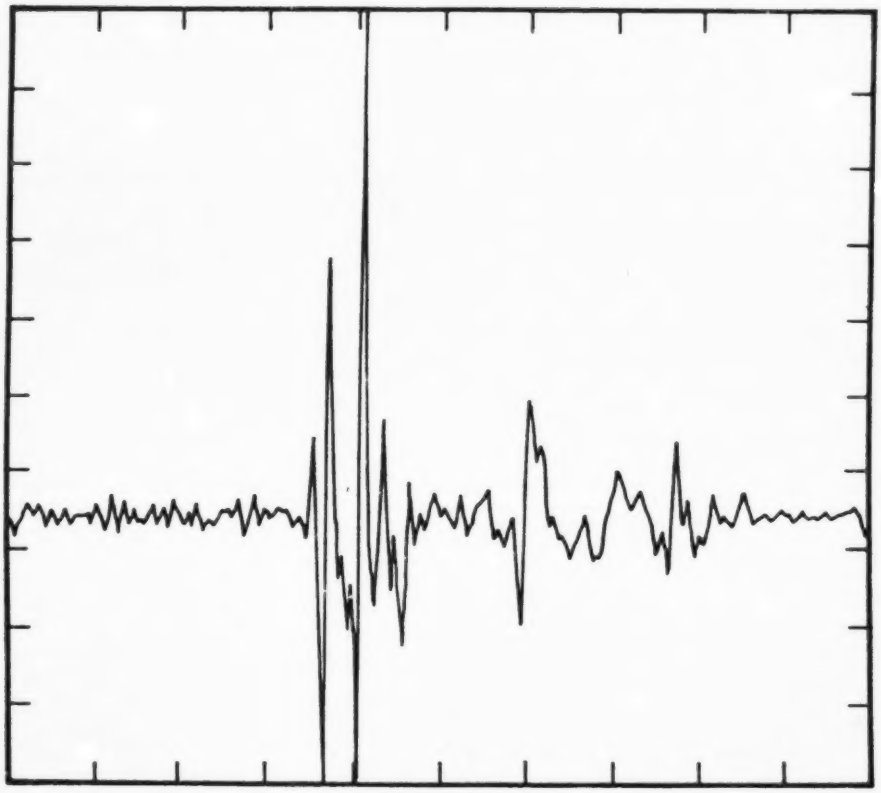
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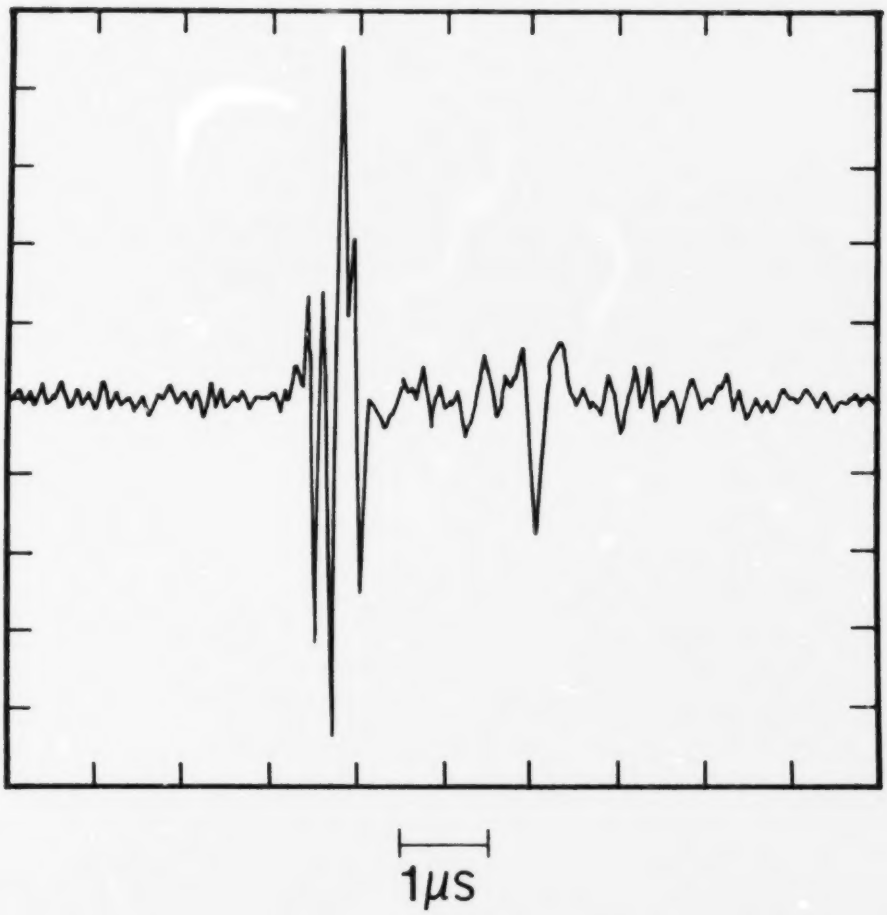
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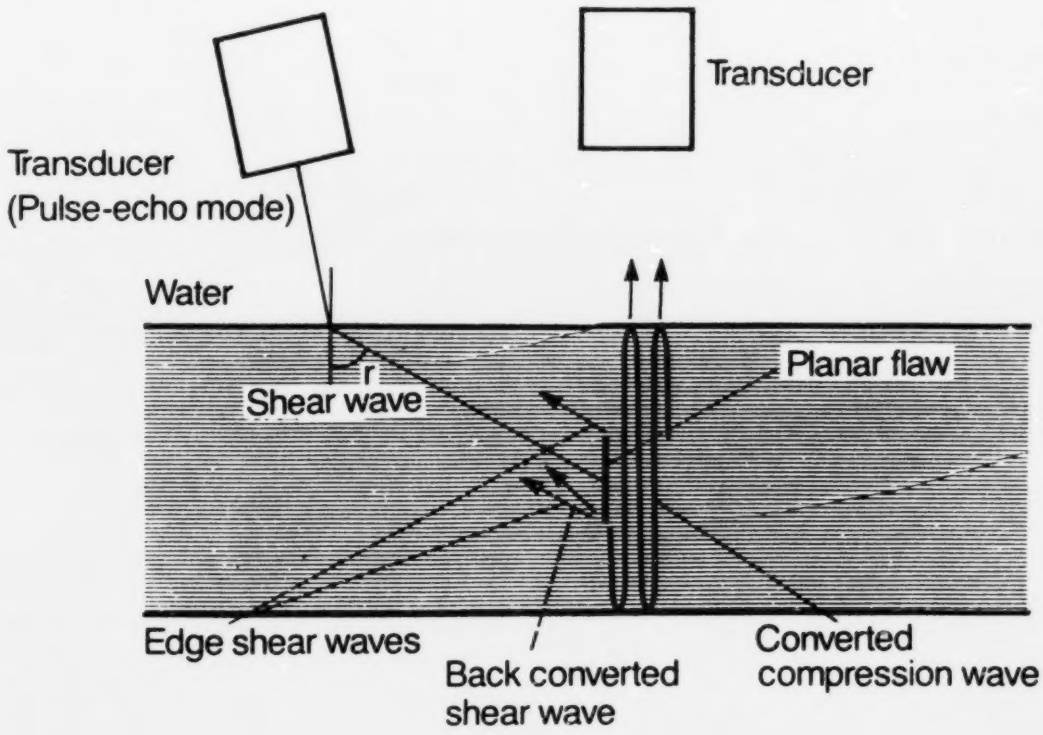
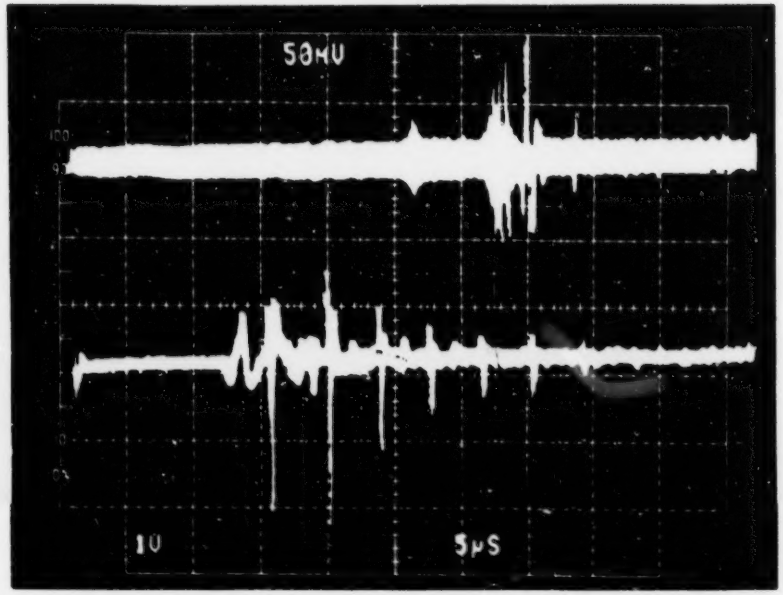

Transducer
Transducer
(Pulse-echo mode)
Water
r
Shear wave
Planar flaw
Edge shear waves
Back converted
shear wave
Converted
compression wave


50mV
1V
5μS